

GAS TURBINES—SOME METALLURGICAL CONSIDERATIONS INVOLVED IN THEIR MANUFACTURE

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ABSTRACT. With the use of jet aircraft, the gas turbine has taken the role of a militarily strategic equipment. This paper deals with the studies of the gas turbine from a metallurgical point of view. The properties of the present day material, used in its manufacture, are reviewed. A new material has been studied for this purpose, which is believed not only to give better service, but will lead, in addition to the design of better gas turbines. That product has been made from raw material abundantly available in India.

It has long been recognised that the internal combustion turbine or gas turbine, as it is more usually called, was the ultimate form into which the internal combustion engine was likely to develop.

In a simple gas turbine air is drawn into the compressor where it is compressed and passed on to the combustion chamber in which fuel is burnt continuously in the excess air. This raises the temperature and pressure of the excess air and products of combustion which are then allowed to expand through the turbine to exhaust. The heat in the exhaust gas from the turbine is used to preheat the compressed air on its way to the combustion chamber.

The compressor, which is directly connected to the turbine and is driven by it, may be of the axial flow, centrifugal, positive displacement lobe type or a combination of these forms.

The efficiency simple gas turbine can be increased by the adoption of any or all of various standard expedients of which the more important ones are :

(1) Increasing the turbine inlet temperature by bringing more fuel per pound of air. This gives an increased output from the same size of plant and markedly improves the fuel consumption.

(2) Improving the efficiencies of any or all of the individual units in the cycle *e.g.*, the compressor, turbine or combustion chamber.

(3) Using one or more interstage coolers to reduce the temperature of the air entering the latter stages of the compressor. The cooled air has lesser volume enabling it to be compressed in a smaller compressor with less expenditure of energy. The heat withdrawn in the intercooler has admittedly to be replaced by the burning of more fuel but this apparent disadvantage is more than outweighed by the saving in the compressor horse power, which appears as additional net horse power output from the plant.

(4) Reheating the gas in the course of its expansion by passing it through one or more combustion chambers, fitted between successive turbine stages. The reason why this gives additional power is obvious.

It is frequently both convenient and advantageous to subdivide one or more of the units in a gas turbine installation. There are many ways in which this can be done, possibly the simplest case being the sub-division of the combustion chambers in air-craft jet engines, which often have as many as ten or more small combustion chambers operating in parallel. The advantage of this lies in the better engine lay-out it provides with reduced overall installation diameter and more uniform distribution of the high temperature gases entering the turbine.

The turbine itself may be sub-divided into two or more separate units *e.g.*, two turbines operating in series. The high pressure turbine drives the compressor and is on a separate shaft from the low pressure turbine developing useful power. Such an arrangement is used for ship propulsion, as it allows the compressor and compressor turbine to be run upto speed before the propeller has got under way.

In general, the efficiency of a gas turbine depends on the basic cycle efficiency of the installation and the efficiency of the individual units. The basic cycle efficiency is inherent in the design, whereas, the individual efficiency depends on the condition of the equipment and the amount of intelligent maintenance given to it.

Of all methods of improving gas turbine efficiencies, the raising of maximum gas temperature is at once the simplest, the most effective and the most reliable.

The heart of the gas turbine is the rotor assembly and it is in the provision of suitable materials for the rotor or disc and the rotor blades that the metallurgists' biggest problem lies. Rotor blades call for a combination of properties not encountered in any other engineering device. In the first place, the temperature at which the blades operate is now generally of the order of 700°C or even more.

Good high temperature properties are required ; but something more needed. The material must have certain desired characteristics at room temperature and must have these qualities every time, for uniformity is one of the most important requisites for highly stressed parts.

Oxidation and corrosion resistance are perhaps the most important requirements. If they are oxidised or scaled or fail due to intergranular corrosion, they are no good. Load-carrying ability is the next essential. The property is measured by short time tensile tests at elevated temperatures, by the creep rate and by the stress required to rupture in a given number of hours at the desired temperature. Of these three tests, stress to rupture is the most widely used. Such a data must always be accompanied by stress-elongation curve that shows how much the sample deforms under the load. A metal which will carry the necessary load for 1000 hours without rupturing

may, nevertheless, be useless for gas turbine parts if it were to stretch so much on application of the load that all clearances are destroyed.

The conventional creep test, with both stress and temperature constant, does not offer enough data for design purposes. Creep rate is normally understood as only the minimum value of stretch under continued constant load, but the initial deformation and the onset of third stage creep may be of equal importance. A series of stress-rupture curves for different temperatures with stress plotted against time and another with stress plotted against elongation give a good idea of load carrying ability.

Structural ability is the next requirement. The material must retain its characteristic structure during exposure to heat and stress or else undergo definite predictable changes.

As nearly all parts of gas turbines are subject to vibration, the fatigue strength of metals at elevated temperatures is another requisite. Good damping capacity is preferred for blades, because a blade of high internal damping tends to inhibit the building up of resonant vibration.

In addition to the above qualities, the material for service in gas turbines must be capable of assuming the desired shape, either through machining, forging or casting and of being joined to other parts either mechanically or by welding.

A large number of alloys have been developed during recent years for service at high stresses and high temperatures mostly for use in gas turbines, jet engines and turbo-super-charges. There are some six or seven alloy groups which have been used for this purpose. They are given in the following table showing the more familiar alloy name, and the composition (Research Memorandum, 1947.)

The alloys fall roughly into the following classes :

(1) Stainless steel types with somewhat increased alloy content, such as 19-9 DL, Timken 16-25-6 ; they are essentially Fe-Cr-Ni alloys,

(2) Highly alloyed stainless steel types such as S-495, Refractalloy B ; these are also essentially Fe-Ni-Cr alloys,

(3) Modified stainless steel types wherein cobalt is found in large amounts ; these are essentially Ni-Cr-Co-Fe base alloys such as N-155 or S-590,

(4) Stellite type alloys such as Vitallium which was one of the first of this group ; these are essentially Co-Cr-Mo or Cr-Co-W alloys.

(5) Modified stellite type alloys wherein certain elements are used in increasing amounts notably nickel, tantalum, columbium, tungsten, carbon, etc., such as X-40, 73 J, and others.

(6) Inconel or Chromel or N-chrome types such as Inconel X and Nimonic 80. These are essentially Ni-Cr base alloys which can be made age-hardenable by additions of titanium etc.

An additional group of considerable interest are the chromium base alloys such as CM 469. They are, however, not yet practical alloys because of extreme brittleness, but may eventually be developed into extremely high temperature alloys.

Table II lists, as far as possible, some of the tensile data from 70° to 2000°F for the high temperature alloys of Table I. There are also given some of the representative complete test results for various test temperatures as well as the particular treatment which gave the alloy its properties. These values are neither optimum nor the minimum values and it must be realised that below about 1300°F many other values might be attained, especially among the forged group of alloys. Above about 1300°F the values listed generally are those for the alloy in its optimum condition for maximum rupture life and resistance to creep at the higher temperatures. It can be noted from the table that the forged alloys show superior tensile properties above 1350°F. (ASTM, 1946.)

Creep tests require such a long time for completion of tests that only a small number have been run. Table III gives the stress to obtain various creep rates for temperatures from 1200°F. Practically all of the tests were run for a minimum of 2000 hours. Actually 2000 hours is not sufficient time to establish a minimum creep rate in a test capable of enduring 20,000 or more hours under load, but from practical aspects the value is satisfactory. Some results obtained in 10,000 hours creep tests carried out at the U.S. Naval Eng. Expt. Station are given in Table IV. (Bureau of Ships Research 1947). These tests indicate that the materials will last at least 10,000 hours. The creep rate at 2000 hours is definitely greater than it would be at 10,000 hours, provided third stage creep had not begun.

At 1200°F, K42B is the best of the three alloys tested. At 1350°F alloys S-590 and high carbon N-153 show the best creep resistance. At 1500°F Refractalloy shows the highest value. Alloys S-495, high carbon N-155, S-497, and S-590 show similar creep results. It might be pointed out that the alloys S-495 and S-497 contain only about 15% Cr. Their oxidation and corrosion resistance at 1500°F and above is not so good as that of the 20% or more Cr. alloys. The cast alloys with few exceptions show much higher creep resistance than do the forged alloys at 1500° and 1600°F.

At 1500°F the stress to cause a creep rate of 1% in 100,000 hours varies from about 5000 lb/sq.in. for Vitallium to 15000 lb/sq.in for alloy 108 N-2. Alloys 93 N-2, 100 NT-2 and 108 N-2 show stressess of 13000 to 15000 lb/sq.in. for a creep rate of 1% in 100, 000 hours at 1500°F.

TABLE I

Alloy Name:	Composition of the Alloy:								Remarks.	
	C.	Mn.	Si.	Cr.	Ni.	Co.	Mo.	W		Others
L ₁ T ₁	0.3	0.6	0.6	13.9	33.2	10.8	3.5	2.3	Balance Fe	Forged.
H-418	0.4	1.5	0.6	15.4	24.5	25.1	3.3	2	Fe, Bal.	Forged.
H-355	0.3	1.5	0.6	20.6	25.1	25.7	3	—	Fe, Bal.	Forged.
H-439	0.4	1.5	0.6	20.4	29.6	31.3	5	—	Fe, Bal.	Forged.
S-495	0.5	0.7	0.7	15	20	—	4	4	Cb ₄ , Fe Bal.	Forged.
Gamma columbium	0.4	0.7	1.8	15	24	—	4	—	Cb ₄ , Fe Bal	Forged.
Vitalium	0.2	1	0.6	23	—	64	6	—	—	Cast
422-19	0.1	0.5	0.5	25	16	52	6	—	Fe 0.65	Cast
Timken 16:25:6	0.1	1.5	0.9	16	25	—	6	—	N ₂ 0.07, Fe Bal	Forged.
Refractalloy B	0.1	2	—	25	30	—	8	—	Fe Bal	Forged.
N-153	0.4	1.8	0.5	16	15	13	3	2.2	Cbr, N ₂ 0.07, Fe Bal	Forged.
N-154	0.3	1.6	0.7	16	24	21	3	2.2	Cbr, N ₂ 0.07, Fe Bal	Forged.
N-155	0.4	1.5	0.7	20	20	20	3	2.2	Cbr, N ₂ 0.15, Fe Bal	Forged.
N-156	0.3	1.5	0.6	16	33	24	3	2.2	Cbr, N ₂ 0.04, Fe Bal	Forged.
Nimonic 80	0.04	0.6	0.5	21.2	74.2	—	—	—	Al 0.61, Ti 2.4	Forged.
8685-2	0.4	2.1	1.6	18.7	15.1	19.7	2.7	—	Cbr.25, Ta 0.9 Fe Bal	Forged.
8658-1	0.4	2.1	1.7	19.1	15.1	19.9	2.6	—	Cb 0.7, Ti 0.5, Fe Bal	Forged.
S-497	0.4	0.5	0.6	15	20	20	4	4	Cb ₄ , Fe Bal	Forged.
19-9DL	0.3	0.5	0.7	19	9	—	1.3	1.2	Cb 0.4, Ti 0.2, Fe Bal	Forged.
X-41	0.5	0.5	0.5	25	8	55	—	7.5	Cr B ₂ 1.8	Cast
ATV-3	0.4	1.4	1.2	15	27.4	—	—	4.0	Fe Bal	Forged.
N-153 (no Co)	0.4	1.5	0.7	16	15	—	3	2.2	Cbr, N ₂ 0.12, Fe Bal	Forged.
N-155 (no Co)	0.4	1.6	0.8	21	21	—	3	2.2	Cbr, N ₂ 0.14, Bal Fe	Forged.
N-155 (modified)	0.4	1.8	0.7	21	21	—	3	2.2	Cbr, Ta 1.1, N ₂ 0.12, Fe Bal	Forged.
TE	0.1	0.7	0.5	20	30	—	4	4	Ta 1.5, N ₂ 0.15, Fe Bal	Forged.
61 (Cast)	0.4	0.3	0.6	24	—	68	—	6	—	Cast
Refratalloy	0.1	2	0.2	20.3	20.1	30.2	8.3	3.8	Fe 15.3	Forged
6059	0.5	0.2	0.8	26	33	34	6	—	—	Cast
X-40	0.5	0.6	0.7	25	10	55	—	7	Fe 0.6	Cast
X-50	0.8	0.6	0.5	23	20	40	—	12	Fe Bal	Cast
S-590	0.5	0.9	0.6	20	20	20	4	4	Cb ₄ , Fe Bal	Forged.
S-816	0.4	0.6	0.3	20	20	45	3	4	Cb ₄ , Fe Bal	Forged and cast
K42B	0.66	0.7	0.3	18	42	22	—	—	Al 0.5 Fe, 13, Ti 2.6	Forged.

TABLE I (contd.)

Alloy Name:	Composition of the Alloy									Remarks.
	C.	Mn.	Si.	Cr.	Ni.	Co.	Mo.	W.	Others	
Discaloy	0.03	0.5	0.5	13	25	—	3	—	Al 0.6, Fe 56, Ti 2.3	Forged.
Co-Cr-Ni Base (9Mo)	0.5	0.7	0.7	23	19	Balance	9	—	Fe 0.9	Cast
Co-Cr Base (9W)	0.4	0.7	0.7	23	3.2	Balance	—	8.8	Fe 0.8	Cast
Co-Cr Base (9 Mo.	0.4	0.7	0.7	23	2.9	Balance	9.2	—	Fe 0.9	Cast
Co-Cr-Ni Base (5Mo, 5W)	0.4	0.8	0.7	22.6	18.2	Balance	5.2	5.1	Fe 0.8	Cast
Refractalloy 26	0.03	0.7	0.7	18	37	20	3	—	Ti 3, Al 0.3 Fe Balance	Forged.
Hastelloy B	0.05	0.6	0.2	—	65.1	—	28.6	—	Fe 4.7	Forged.
Inconel X	0.05	0.5	0.4	14.6	73.4	—	—	—	Cb1, Fe 6.9, Cu 0.04, Ti2.3, Al 0.7	Forged.
Stellite 6	0.08	1.0	0.7	32	—	60	0.6	4.6	—	Cast
GT-45	0.08	1.25	0.5	17.3	13.8	—	2.9	—	Cb 0.45, Ti 0.3, Cu 3.1, Fe Bal	Forged.
MT-17	0.06	1.5	0.5	21	30	21	3	2.2	Ti 1.6, Fe Bal	Forged.
31 V4	0.31	4	—	23	—	65	6	—	—	Cast
100 NT-2	1	1.5	0.5	20	30	20	3	2.2	Ta 2, Fe Bal	Cast
36 VT 2-3	0.36	2	—	23	—	65	6	—	Ta 2	Cast
110 N-2	1.10	1.5	1	21	30	21	3	2.2	Cb1, N2 0.07 Fe Bal	Cast
111 VT 2-2	1.11	—	—	23	—	67	6	—	Ta 2	Cast
73 J	0.73	1	—	23	6	60	6	—	Ta 2	Cast
36 J	0.36	1	—	23	6	60	6	—	Ta 2	Cast
35 H	0.35	1	—	23	2	61	6	3	Ta 2	Crst
CM 469	0.03	—	—	60	—	—	25	—	Fe 14	Vacuum cast

TABLE II

Trade Name:	Temp. °F	Tensile stress lb/Sq. in:	0.2% yield lb/sq. in:	Properties limit lb/Sq. in:	% Elongation:	% R of A	Treatment:
LCN-155	Room	146,750	121,000	70,000	25.5	47	10% CW-1200°F
	1200	116,000	0.1% Yield		13	23	10% CW-1200°F Hot worked
	1350	80,940	65,650		24	37	2300°F-3/4 Hr-WQ
HCN-155	1500	49,400	29,000		34	35	1500°F-4 Hr-FC
	Room	138,000	70,600		16	12.6	2200°F-1 Hr-WQ
	1500	58,000	29,000		34.2	28.8	1500°F-4 Hr-FC
S-590			0.2% Yield.				
	Room	160,500	89,500	30,000	10	10.5	2270°F-1 Hr-WQ, 1100°F-16 Hr
	1200	81,600	49,000		27	31	2300°F-1 Hr-WQ, 1400°F-16 Hr AC
K 42 B	1300	66,875	58,500	22,000	27	33	2270°F-1 Hr-WQ, 1400°F-16 Hr
	Room	162,500	97,200		31.0	39.4	1750°F-1 Hr-WQ
	1200	128,000	91,250		10.0	13.3	1200°F-72 Hr-FC
Hastelloy B	1350	101,000	79,700		6.5	10.2	
	1500	71,000	41,250		2.5	4.2	
	1700	23,900			40.5	66.0	
	Room	139,200	57,000		49.5	51.1	1950°F-2 Hr-AC
	1500	77,500	42,500		27.0	21.2	1950°F-2 Hr-AC
	1600	52,500	39,700		48.0	41.7	
S-816 Forged	1700	39,000	28,400		45.0	51.8	
	1800	31,500	16,100		62.0	53.5	1950°F-2 Hr-AC
	1900	18,500	9,800		70.0	53.0	
	2000	13,100	7,600		54.5	46.9	
			0.2% Yield.			...	
	Room	175,000			39	45	As rolled
	1200	120,200			17	22	2300°F-1 Hr-WQ,
	1350	98,900			15	22	1400°F-AC

TABLE II (contd.)

Trade Name:	Temp. °F	Tensile Stress lb/sq. in	0.1% Yield lb/sq. in	Properties limit lb/sq. in	% Elongation:	% R of A	Treatment
S-816 Forged	Room	175,000	0.2% Yield.		39 17 15 12 18 14	45 22 22 21 20 17	As rolled. 2300°F—1Hr—WQ, 1400°F—AC
	1200	120,200					
	1350	98,900					
	1500	78,266					
	1600	59,770					
Nimonic 80	1700	46,180					
	Room	153,000	83,800	75,000	36.5	33.6	1950°F—2Hr—WQ, 1300°F—16 Hr. Finish Forge 1400°F Finish Forge 1400°F
	1200	97,500	77,000	30,000	14.5	20.8	
S-497	Room	154,750	138,500	57,500	10.5	20.5	
	1200	103,625	89,800	15,000	22	25.9	
			0.1% Yield.				
Inconel 'X'	1300	64,400	36,000		35 6.5 19.5	32.0 8.6 18.4	2100°F—1Hr—WQ, 1500°F—4Hr—FC.
	1500	63,400	40,400				
	1700	28,000	16,000				
	Room	192,000	136,000				
	1200	118,000					
S-495	1500	70,000					
	Room	147,750	136,000	35,000	26	45	Hot rolled—aged Hot rolled—solution treated—aged. Finish forged 1400°F
	1200	87,625	72,200	37,500	12	14	
					3	10	
					6.0	21.7	
			0.1% Yield.		24.0	34.3	
Gamma Colum- bium. N-156	Room	107,500	46,000		26.0 36.9 32.0	30.1 42.2 33	2250°F—3/4 Hr—OQ, 1500°F—50Hr 2200°F—1Hr—WQ—4Hr—1500°F—FC
	1500	43,500	23,000				
	1500	55,000	30,000				

TABLE II (contd.)

Trade Name :	Temp. °F	Tensile stress lb./sq. in. :	0.2% Yield lb./sq. in. :	Properties limit lb./sq. in. :	% Elongation :	% R of A	Treatment :
ATV-3	Room	121,700	84,000		21.5	36.5	As rolled.
	1200	75,200	46,000		25.0	32.2	
	1350	66,000	30,750		28.0	39.4	
	1500	42,600	15,100		31.0	38.5	
19-9 DL Timken	1700	24,100			38.5	43	2100°F—1Hr—AC Finish roll 1200°F, Stress relieve 1200°F—AC 2100°F—1Hr—AC Finish roll 1200°F—AC Stress relieve 1200°F—AC
	Room	140,750	115,000	75,000	29	48.1	
	1200	91,000	51,000	52,500	16	38.8	
	Room	162,250	143,500	102,500	15.5	33.6	
16-25-6	1260	107,500	94,000	60,000	13.0	27.9	Preheat 1500—1550°F, 2150°F—WQ 2160°F—2Hr—WQ 2160°F—2Hr—WQ Hot rolled—1200°F—5Hr
	1350	60,100	27,000		40.0	35.5	
	1500	48,300	31,400		27.5	26.2	
	1800	21,000	12,000		22.0	19.5	
GT-45	Room	101,500	61,200	38,700	30	54.4	Hot rolled—1200°F—5Hr
	1200	66,500	47,500		27	48.2	
	1350	51,000	35,800	22,000	37	44.1	
	1500	36,000	24,000	15,500	19	16.7	
Vitalium	Room	110,000	65,000	55,000	10	12	As cast 1350°F—48Hr. As cast
	Room	120,000			5.1	6.6	
	1200	71,000	35,600	25,200	18.4	41.5	
	1350	93,200	71,500	39,300	1.8	5.6	
	1500	76,000	59,300	36,100	3.5	8.2	1350°F—50 Hr.
	1600	82,700	63,700	33,200	4.0	9.8	
	1700	57,300	47,350	23,300	8.3	19.7	
	1800	61,400	50,700	28,100	5.3	4.5	
	1700	49,200	35,000	22,200	9.8	15.8	As cast As cast 1700°F—16Hr, AC
	1800	48,600	36,800	19,400	19.9	19.9	
		42,470			27	52.4	
		33,265			35	52.4	
		32,910			49	63.1	

TABLE II (contd)

Trade name:	Temp. °F	Tensile stress lb/sq. in.	0.2% Yield lb/sq. in.	Properties limit lb/sq. in.	% Elongation	% R of A.	Treatment
6059	Room	82,550	46,900		7	10.3	As cast
	1200	76,800	41,100	24,200	3	3.4	1700°F-16Hr-AC
		46,300	34,400	21,500	3.3	7.7	As cast
	1350	51,500	35,600	30,600	4.2	8.2	As cast
			51,900	32,100	—	4.6	
	1500	66,200	49,800	26,000	3.2	21.8	1350°F-50Hr.
		51,400	38,700	20,900	12.0	7.0	
	1600	51,000	37,700	13,700	8.3	20.8	
		41,500	31,200	19,500	10.0	19.4	
	1700	41,200	30,500		13.0	26.5	As cast
422-19		42,950			23	34	1700°F-16Hr-AC
	1800	45,430			16	50.3	As cast
		33,400			24	41.7	1700°F-16Hr-AC
		33,590			26	11.9	As cast
	Room	98,100	55,100		5	0.65	1700°F-16Hr-AC
		94,500	56,200		1	15.7	As cast
	1200	58,300	36,900	19,500	7.2	10.3	As cast
		62,000	38,400	24,700	7.0	2.1	
	1350	74,800	59,000	38,300	2.0	3.3	
		80,700	63,800	40,000	1.6	3.3	
61	1500	65,000	49,500	29,400	2.7	3.3	1350°F-50Hr.
		63,000	45,700	23,700	3.3	15.8	
	1600	49,200	35,000	22,200	9.8	19.9	
		48,600	36,800	19,400	9.5	26	As cast
	1700	45,180			17	33.3	1700°F-16Hr-AC
		47,135			18	33.7	As cast
	1800	36,290			24	38.7	1700°F-16Hr-AC
		37,800			21	11.2	As cast
	Room	103,400	58,350		7	14.2	1700°F-16Hr-AC
		108,500	53,900	21,900	6	18.4	As cast
61	1200	79,500	39,000	37,300	14.0	5.8	
		103,400	74,000	34,500	2.1	5.0	
	1350	73,600	61,000	34,500	1.2	7.9	
		85,600	65,200	23,900	2.8	16.1	
	1500	59,500	40,000	25,100	7.4	9.3	1350°F-50Hr.
		57,500	41,200	14,500	8.2	14.8	
	1600	46,800	34,200	18,000	9.6	18.8	
		44,800	32,000		10.0		

TABLE II (contd)

Trade name :	Temp. °F	Tensile stress lb/sq. in.	0.2 % Yield lb/sq. in.	Properties limit lb/sq. in.	% Elongation:	% R of A :	Treatment :
61	1700	37,475			7	35.7	As cast.
		43,580			18	35.7	1700°F—16 Hr—AC.
	1800	33,115			32	40.6	As cast.
X-60		33,050			27	30.5	1700°F—16 Hr—AC
	1500	61,000	53,500	22,800	1.0	mil	1500°F—50 Hr.
	1600	54,000	39,200	13,600	1.5	2.1	1600°F—50 Hr.
		50,000	37,000	12,900	1.4	1.1	1500°F—50 Hr.
X-40	Room	101,000	74,100		11	14	As cast.
	1200	76,800	37,400	23,400	18	28.1	As cast.
	1350	77,300	37,800	22,300	20	28.6	As cast.
		82,200	53,400	31,300	7.0	8.1	
		69,200	53,800	33,100	2.3	7.0	
	1500	57,500	42,500	26,200	14.0	15.4	
		61,400	47,500	32,400	5.0	12.1	1350°F—50 Hr.
	1600	48,500	35,200	22,900	14.3	18.1	
31 V-4		48,500	37,300	24,000			
	Room	135,300			3.3	6.0	1350°F—48 Hr.
	36 VT2-3	102,800			5.9	10.7	As cast.
	Room	120,000			10.2		As cast.
70 J	Room	111,000			3.0	1.5	As cast.
	Room	120,000			3.8	1.0	As cast.
	111 VT2-2	100,000			1.5	1.0	2260°F—WQ
	Room	112,000	59,000		5	13	As cast.

TABLE III

Creep rate data for forged and cast alloys from 1200°F to 1600°F :

Alloy :	Temp. °F	Stress for minimum creep rates, % per hour of :			Alloy	Temp. °F	Stress for minimum Creep rates, % per hour, of:		
		0.001	0.0001	0.00001			0.301	0.0001	0.00001
Hastelloy B	1200	20,000	7,400	2,650	Vitalium NR-90	1500	11,700	7,600	4,900
Timken	1500	4,800	2,800	1,600		1600	11,200	7,900	5,600
	1200	21,500	14,000	9,000		1500	10,900	12,500	7,900
K 42 B	1500	8,400	5,700	3,800	6059	1500	15,000	11,700	9,000
	1200	29,000	18,800	12,000		1600	11,000	9,000	7,300
19-9 DL	1500	14,000	7,400	3,900	422-19	1500	18,400	13,200	9,500
	1500	10,400	7,100	4,800		1600	14,500	11,600	9,500
Nimonic 80	1500	15,700	9,500	5,700	61	1500	17,000	13,000	10,000
Refractalloy 26	1500	15,700	9,500	5,700	X-50	1500	18,200	13,500	10,100
	1500	9,800	8,300	7,000	73J	1600	13,300	10,500	8,500
N-155 (LC)	1350	25,000	18,400	13,500		1500	20,400	14,300	10,100
N-155 (HC)	1500	13,800	10,300	7,800	X-40	1600	18,500	13,700	10,200
S-590	1350	12,700	10,000	14,300		1500	15,700	11,700	8,700
TE	1500	9,600	9,600	7,300	111 V12-2	1600	22,400	15,000	11,000
Inconel X	1500	19,600	9,500	7,500	93N-2	1500	15,100	10,300	7,200
	1500		12,300	7,600	100NT-2	1500	21,100	16,700	13,000
S-816	1350	26,800	18,000	12,200		1600	21,800	17,400	13,800
	1500	16,400	11,500	8,100	110N-2		16,000	11,700	8,500
	1600	8,500	5,800	4,000					
S-497	1350	19,700	15,800	12,800					
	1500	12,400	10,000	8,100					
	1600	7,800	6,200	5,000					
S-495	1350	22,400	16,100	11,700					
	1500	12,900	10,400	8,300					
	1600	7,900	5,300	3,500					
Refractalloy	1500	15,200	12,800	11,000					

TABLE IV
10000 Hour Creep Tests at 1500°F

Alloy	Heat Treatment	Stress lb/sq in	Creep rate % per hour at		Final reading	Length of test, hours
			1000 hours	2000 hours		
92 N-2	2260°F - WQ	10,000	0.000392	0.00040	0.0000015	6,500
N-155	2300°F - WQ	8,500	0.000011	0.000018	0.0000022	10,078
S-816	2350°F - WQ	8,500	0.00003	0.000029	0.000113	10,103

These alloys are all high carbon modifications of N-155, which as a low carbon forged alloy, shows good creep resistance. These alloys are the nickel-chromium-cobalt-iron base compositions as are S-500, S-497, and S-495. Compared to the cobalt-chromium base alloys the former are much superior in creep, but generally poorer in rupture (short time) properties. The best cast cobalt-chromium base alloys at 1500°F show 5000 to 11000 lb/sq.in. for a creep rate of 1% per 100,000 hours. Except for Vitallium, which shows the lowest creep resistance, the stress for a creep rate of 1% per 100,000 hours at 1500°F is fairly constant at $10,000 \pm 1000$ lb/sq.in. for 111 VT 2-2, X-40, alloy 61, X-50, 73 J, 6059 and 422-19. At 1600°F, X-40 and 100 N-1-2 show the best creep resistance at creep rates of 0.0001% per hour and above, while 422-19 is best in the lower creep rate range.

The above alloys have so far yielded a fair amount of work and have been widely used in turbine blades, jets, venturies and valves at high temperature in air-crafts. There is not, however, very great promise for going further in this direction. The reason lies in the short space between the temperatures at which the alloys are cast or forged into useful shapes and the temperatures at which the finished parts must work in service. For this country there is yet another reason. It is not only economic but strategic as well. All the above mentioned alloys are composed of a very high percentage of metals which are not found in this country, *e.g.*, Ni, Mo, W, Cb, Ta, Co, etc. If gas turbines have to be developed in this country, high temperature materials have to be produced without heavy consumption of these elements which are scarce here.

One has, therefore, to look towards other refractory alloys. Through powder metallurgy combinations of metals may be tried which involve material not very easy to fuse. The hard compounds, which we use for making tools and grinding wheels offer themselves as the most interesting group of promising materials. They could be made into parts by powder metallurgical processes. They are strong in the formed and sintered state and are more erosion and abrasion resistant than pure refractory metals. The borides and carbides of refractory metals (*e.g.*, chromium, molybdenum, tantalum,

columbium, titanium and tungsten) offer a great promise in this field. The author has been experimenting for a fair length of time on titanium carbide and its use for hard cutting tools and for high temperature work. The compound was chosen with a special motive. Titanium is found in fair abundance in this country, in the South as titanium dioxide in ilmenite sand and in the magnetite ore of Mayurbhanj State. The author used the titanium after extracting it from the magnetite ore belonging to Sir Indra Singh, after all the vanadium in it had been extracted in the works of Vanadium Corporation, a sister concern of Tata's. Hundreds of compounds of titanium and carbon were made during the course of experiments and a variety of binding media employed. The properties given below belonged to one particular compound and one particular percentage of the binding medium, which gave the most promising high temperature properties.

Titanium carbide was made in an experimental electric arc furnace and formed into shapes of test rods by the method of powder metallurgy. The carbide was powdered and mixed with finely divided cobalt. It was cold pressed into shape at a pressure of 30 ton./sq.in. and sintered in a graphite furnace at about 1675°C. It was tested at high temperature with the following results:

*Tensile strength at about 1000°C	...	...	8 T/sq.in.
*Transverse strength at about 1000°C	..	...	40 T/sq.in.
Specific gravity	...	...	5.5
Thermal conductivity, calories/sec/°C/cm	...	...	0.09
Hardness [Diamond Pyramid Scale (50 Kg. load)]	...	...	1600

Creep strength could not be determined of this material as no instrument was available.

There was no apparent attack to combustion gases up to 1150°C in 48 hours, nor was there any loss of strength. The material withstands drastic

* The apparatus in which the material was tested for transverse or tensile strength at 1000°C consisted of 5" x 6" x 6" platinum-wound furnace which was slipped on the specimen. This permitted the heating of the specimen to 1350°C with less than 5°C difference in temperature over the length of the test section. The load was applied by means of four jawchucks. There were guide rods to prevent misalignment. The entire assembly was mounted on a heavy horizontal bed plate with slots in which the movable head could travel. The heads were hollow cast aluminium and were water cooled. One head was actuated by a hydraulic cylinder operated by hand. The value of the frictional losses was determined by carrying out a blank test with the help of known steel samples with strain gauges attached. The specimens were 10" long and 3/8" in diameter with 1 1/4" long and 1/4" diameter in the centrally thin portion. The tests were carried by applying the load after holding the specimen at the proper temperature for 15 minutes.

For transverse loading, a fused silica edge was placed at the centre of the sample, for which a space was kept in the furnace, and it was loaded hydraulically when the test piece had reached the proper temperature.

thermal shocks. There was no appreciable change in strength when it was heated to about 1000°C and then quenched in water. Air cooling from the same high temperature leaves no effect other than an initial discoloration of the surface. Its thermal conductivity is about $1/10$ that of copper.

The above data show that titanium carbide, properly bonded, could be used as a high temperature material for use in gas turbines and jet engine parts. The author has just started experimenting with a bond of chromium metal. The work has not advanced sufficiently for any data to be furnished. There are two other methods of converting these refractory compounds into finished parts, and there are reasons to believe that at least one process will yield better results than those given above. Those two methods are : (1) hot pressing and (2) infiltration process.

(1) Hot pressing : By this method the pressing and sintering processes are combined and performed at the same time. The applied heat develops greater plasticity of the powders and permits the use of lower pressures (1 Ton/sq.in.). Graphite moulds may be used which is an advantage in the case of the carbide type hard compounds, for reasons of obtaining a protective atmosphere. After the part is formed another sintering at higher temperature may be done to complete the alloying and the fusion of components.

(2) The infiltration process : In this case a porous skeleton is formed of the refractory metal or hard compound phase, and thereafter molten materials of adequately high fusion point are drawn by surface tension into every pore and interstice of the sintered skeleton. The advantage of this method lies in the lower forming pressures, it not being necessary or even desirable to reduce the porosity of the original sintered part to a minimum. Only a small percent of the cementing agent may be mixed in with the original hard compounds. The remainder of the cementing material constitutes the impregnant. This technique promises greatest success from the following considerations.

(a) The skeleton manufactured before infiltration is a continuous matrix and so is the pore system which is later filled with the infiltrants with the help of precision casting (e.g., centrifugal casting, vacuum casting or gas pressure casting). With both systems being continuous, there is a lesser opportunity for internal cracks. Both the operations can be performed by using a single investment mould first for forming the original sintered skeleton and then for making the subsequent infiltration.

(b) There is better controllability of grain size and the possibility of developing uniformly large grain sizes by heat-treatment of the parts after infiltration. This may prove to be of great importance from the stand-point of hot strength and creep resistance.

(c) There is an advantage of making complicated shapes by 'keying together' similar sections and heating the assembly so that the infiltrant fuses and welds the simple shapes together.

(d) There is a possibility of using a slight excess of the infiltrant so that it spreads thinly over the entire surface of the part, thereby effectively covering it with corrosion resistant material. This coating will be continuous and entirely merged with the matrix of infiltrant, which previously has permeated the interconnected pore system of the skeleton thereby preventing spalling.

From its inherent properties, chromium boride appears to show signs of interest. There are a number of borides of chromium, all, at least, as resistant to oxidation and chemical attack as pure chromium. Their basic hardnesses are in the region of 1400-1600 on the diamond pyramid scale. The hardness diminishes only very slightly up to about 750°C, *i.e.*, temperatures now employed in turbines and jet engines. They are highly soluble in such metals as nickel, iron, cobalt or chromium so that the latter materials may be used as cementing agents. Moreover, their specific gravity is low.

There appears to be yet another opportunity of the application of power metallurgical techniques for the production of high temperature material with superior service characteristics. It is in the use of oxides and ceramic compounds. It is already known that specific oxides, such as alumina, can be combined effectively with such metals as nickel and cobalt, possibly with the aid of intermediate bridging metals, such as molybdenum or tungsten.

Considerable work is being done at present in America on similar lines. The work carried on there may be divided into two broad divisions: structural bodies and protective coatings for metals. The first classification includes supercharger buckets, turbine bladings, exhausts nozzles, liners for expendable and recoverable rockets and guided missiles. Although it is felt that these dynamic parts are stressed in a manner usually considered outside the realm of ceramics, studies are nevertheless being made of the theoretical mechanics of brittle materials with a view to possible design to eliminate this limitation.

Coatings for metals have, however, received concentrated attention. It is obvious that one way to extend the temperature range and the resistance to chemical attack of an existing alloy is to provide it with a protective coating. This coating must be sufficiently refractory to withstand service conditions; it must have high resistance to chipping and cracking under repeated thermal shocks and it must be resistant to corrosion and erosion by hot gases and fluids. It should further be capable of easy application to complex shapes.

Gas turbine power plant is composed largely of sheet metal parts, *e.g.*, exhaust stack, tail cones, combustion chambers etc. Some ceramic protective coatings have already been developed which have given very good service and the life of engines has been increased by at least 100%.

It is worthwhile to indicate some of the directions in which this work is being carried out in U.S.A. Attempts have been made to coat alloys by spraying refractory materials through a flame directed on the metal similar

to metallizing process. Investigations are also being carried on the alloying of the metallic constituent of metal bonded ceramic bodies with the surface of the metal to which it is applied. Impregnation of the surface of alloys with refractory oxides through pressure is also being explored.

One of the most interesting work in this connection is that pursued by Armour Research Foundation in collaboration with the Air Material Command of the U.S.A. This research programme involves the study of ternary and quaternary ceramic oxide systems in search of a glass composition which will fuse to a homogeneous mass at a temperature within the normal temperature range of ceramic enamels. The coating is to be applied in either of the two conventional ways, *i.e.*, by sifting the dry material on to the heated metal part, or by dipping the object in a slip or slurry of the ceramic composition.

After the unfired ceramic coating has been applied, the metal object is to be subjected to sufficient heat to cause the ceramic materials to fuse to a smooth adherent coating in the usual manner of porcelain enamels. The enamelled object will then be heat-treated or annealed, causing the glass coating to separate into two continuous, but mutually immiscible phases. One of these phases should be more soluble than the other, so that it may be leached out of the glass structure with acid, leaving the other less soluble, more refractory glass in place on the metal. A third heat treatment or perhaps service conditions should cause the vesicular glass residue to fuse to a smooth thin impervious, highly refractory protective coating.

Essentially this process is similar to that involved in the manufacture, of Vycor, a heat resistant glass made by Corning in U.S.A. In this process a borosilicate glass is melted in a tank, from which it is drawn to form beakers, flasks, crucibles and other chemical wares. After the ware has been moulded, it is annealed to cause separation of the glass into two distinct immiscible phases. Sulphuric or hydrochloric acid is used to dissolve out the more soluble glass, leaving a porous structure composed largely of a thickly silicious glass in the original form of the object. Reheating causes the silica glass to soften slightly well below its melting point, converting the cellular structure to a non-porous, vitreous condition.

The gas turbine is the latest form into which the internal combustion engine has developed. It operates on the same basic thermodynamic cycle as the Diesel engine. Although only Diesel fuel is being used at present for most of the gas turbines, heavier fuels and even pulverised coal will soon be used in them. Even now experiments are conducted in the U.S.A. for the use of pulverised fuel in locomotives fitted with gas turbines. When problems connected with the use of coal for running a gas turbine are solved, it will be in a position to extend its challenge to practically the whole gamut of heat engines within its range of powers which, at the moment, extends from about 1500 to 20,000 H.P. In following up this challenge the gas turbine has the advantage that it may be built in many forms, so that quite

apart from questions of cost or efficiency it is mechanically capable of satisfying the most varied requirements from those of the power units for fighter air-crafts to those of huge turbo-alternators of base load electricity generating stations. Unless some means is found for direct conversion of fission energy, the closed cycle gas turbine* with helium as the working fluid is likely to find extensive use as the most favoured method of power generation from atomic piles. Intermediate and more immediate application of promise include the powering of locomotives and ships.

The future of gas turbine, jet turbines and even perhaps the efficient utilisation of atomic energy rest upon the ability to construct working parts and housings that will function at higher and higher operating temperatures, up to and beyond 1400°C . And at those temperatures the materials must have strength, resistance to creep, resistance to impact and heat shock, corrosion resistance and sufficient hardness to resist the abrasions and erosions of extremely high speed gas streams.

To combine such properties is quite a task which the mechanical engineer, the power engineer and the atomic engineer are anxiously waiting for the metallurgist to fulfil. And fulfil he shall.

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* Gas turbines where the fuel is burnt directly in the working air are known as "open cycle" machines. If, however, it is desired to use some medium other than atmospheric air for the working fluid then this can be done by using a "closed cycle arrangement", where the exhaust gas from the turbine is passed through a cooler and then returned to the compressor inlet, the same gas being used continuously over and over again.

Various gases have been proposed for use as the working fluid in closed cycle machines, but the most popular at present is compressed air. The advantage of using compressed air instead of atmospheric air is that because of its greater density compressed air has better heat conduction and convection characteristics and thus enables heat exchangers and inter-coolers to be made both smaller and more efficient. As a result of large scale atomic fission, helium is expected to be both cheap and plentiful. In that event it will be the gas to be used in closed cycle gas turbines.

The closed arrangement does, therefore, lend itself to the relatively economic production of the more complicated cycles with several stages of intercooling, several stages of reheating, extensive heat exchange etc. Its advantages show up best on large machines of say 30,000 K.W. and above.

The disadvantage is that without these complicated refinements the closed cycle is less efficient than the open cycle and it is, therefore, not altogether suitable for marine or locomotive use where space is at a premium, nor is it attractive for peak load or stand-by plants in which simplicity and low first cost are more important than a slight saving in fuel.

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